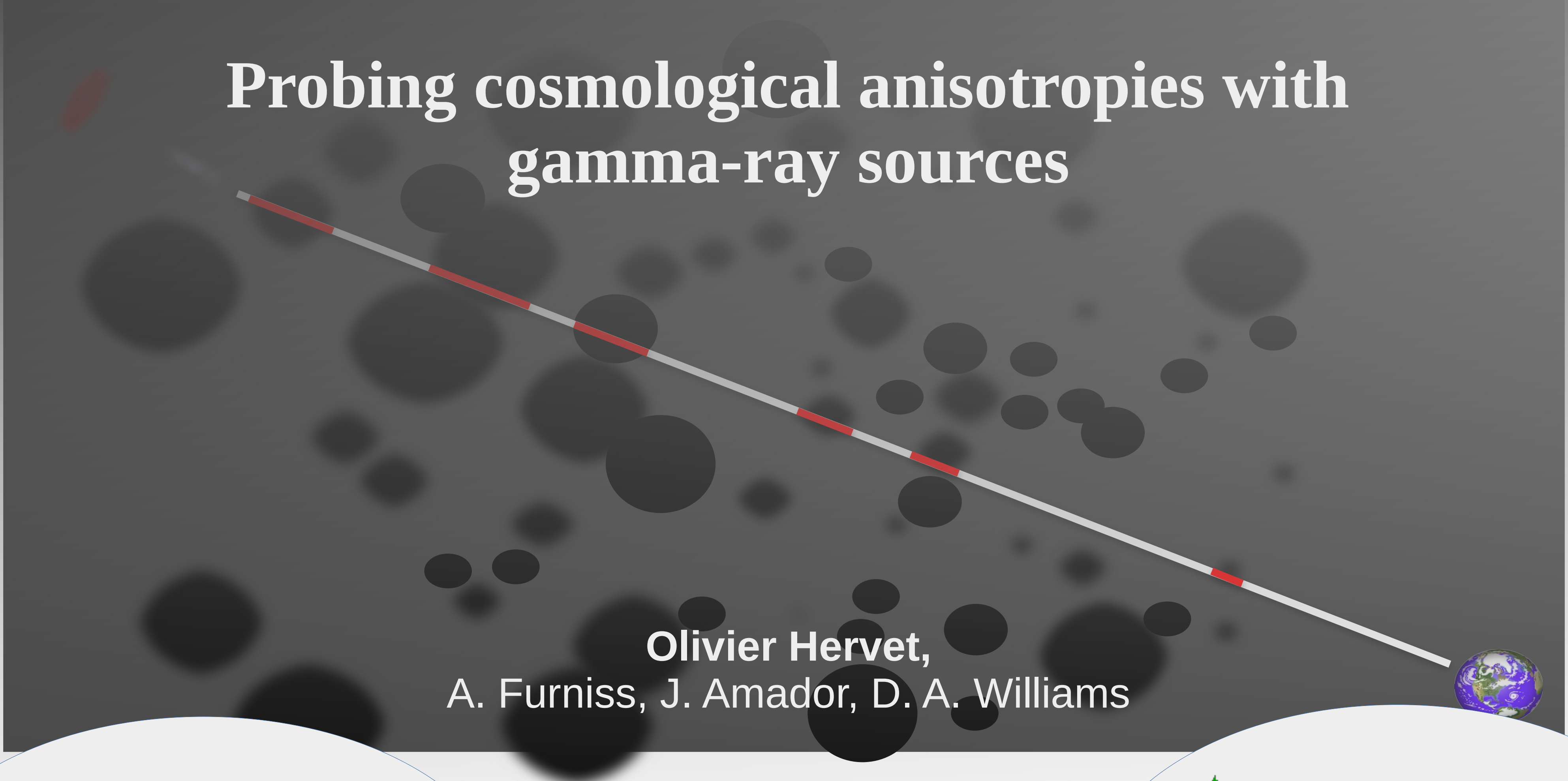
Probing cosmological anisotropies with gamma-ray sources



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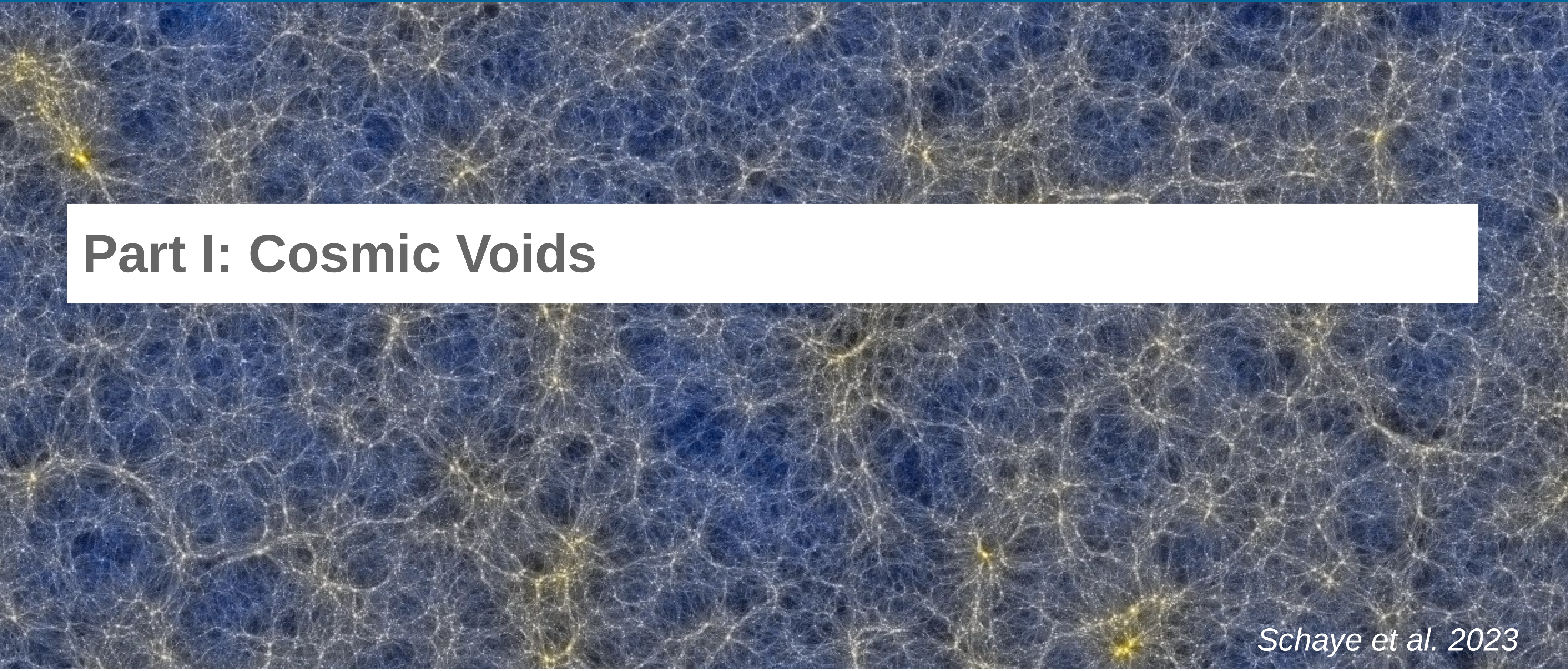
Astroparticle Symposium
Nov. 2024, Institut Pascal, Saclay

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

Image credit: CTA



Part I: Cosmic Voids

Schaye et al. 2023

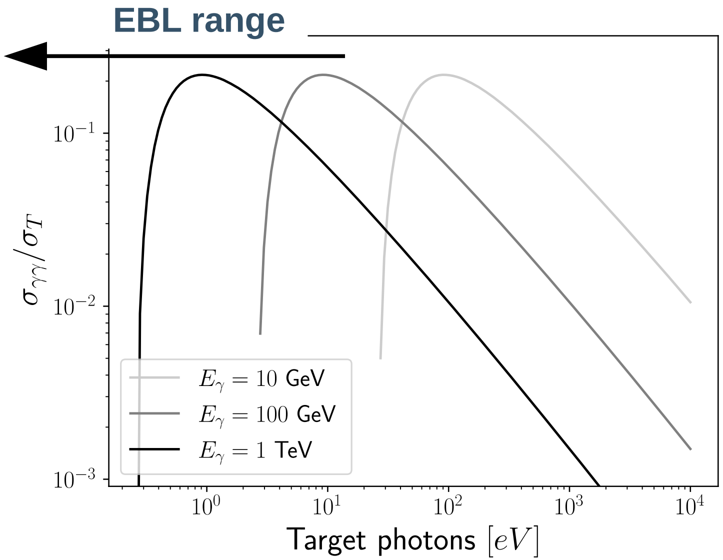
Gamma-ray interactions with the EBL

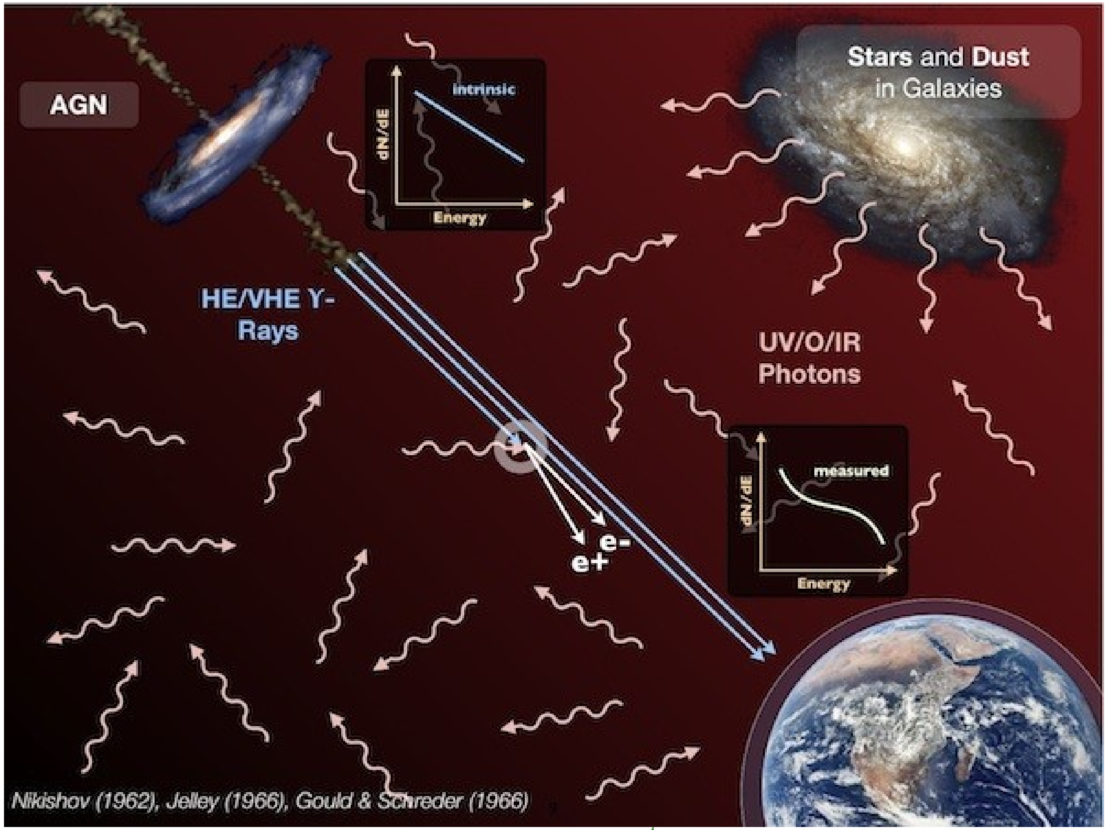
Very high energy gamma-rays have a sweet spot for the EBL

$$\gamma 1 + \gamma 2 \longrightarrow e^+e^-$$

Maximum probability of interaction (cross section) when

$$E_{\gamma 1} \simeq \frac{4m_e^2c^4}{E_{\gamma 2}} \simeq \frac{1}{E_{\gamma 2}[\mathrm{TeV}]}\mathrm{eV}$$





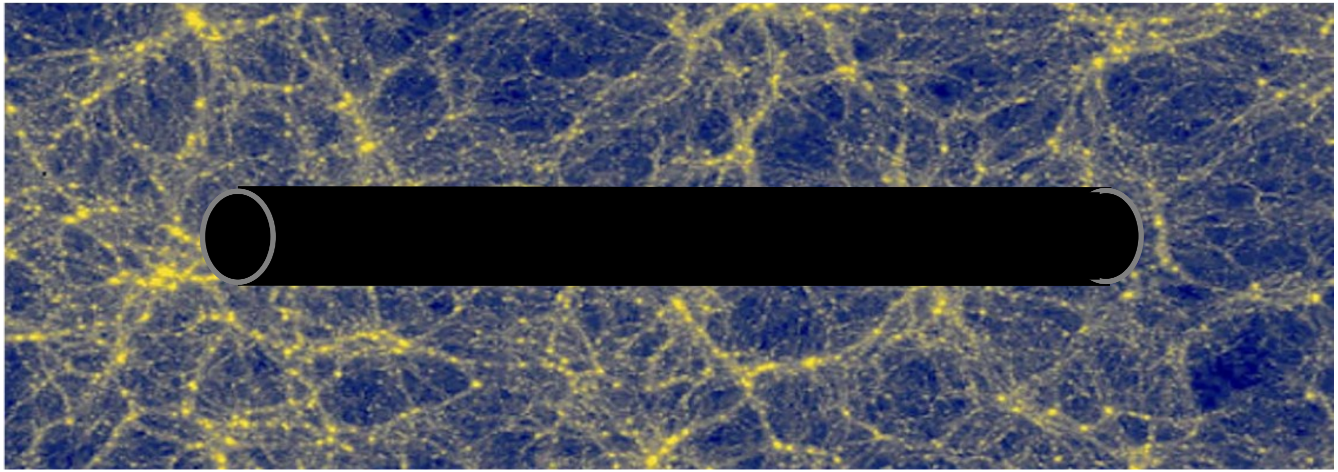
Nikishov (1962), Jelley (1966), Gould & Schreder (1966)

Effects of cosmic voids on EBL

Cosmic voids potentially have lower EBL density
→ Gamma-ray spectra of sources behind voids should show harder spectral index
→ Not observed so far, only upper limits

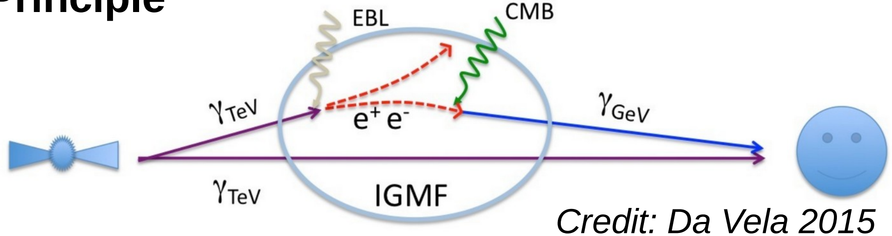
e.g. Furniss, Sutter, Primack & Dominguez, MNRAS 2015

- Simulated a 2000 Mpc tunnel devoid of galaxies
- EBL photon density within tunnel changes by < 2%.
- Decreases gamma-ray/EBL pair production by 10%.



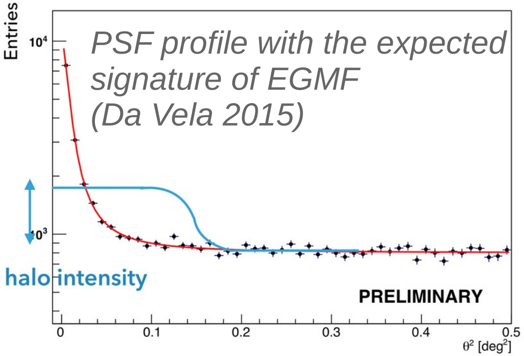
Probing Extragalactic Magnetic field with Gamma-rays

Principle



Credit: Da Vela 2015

- After pair creation on the EBL, e+e- are deflected by the EGMF
- Compton interaction over CMB photons re-produce gamma-rays but from a slightly different direction
- **pair-halo (PH)** and **magnetically broadened cascade (MBC)** could be seen around blazars

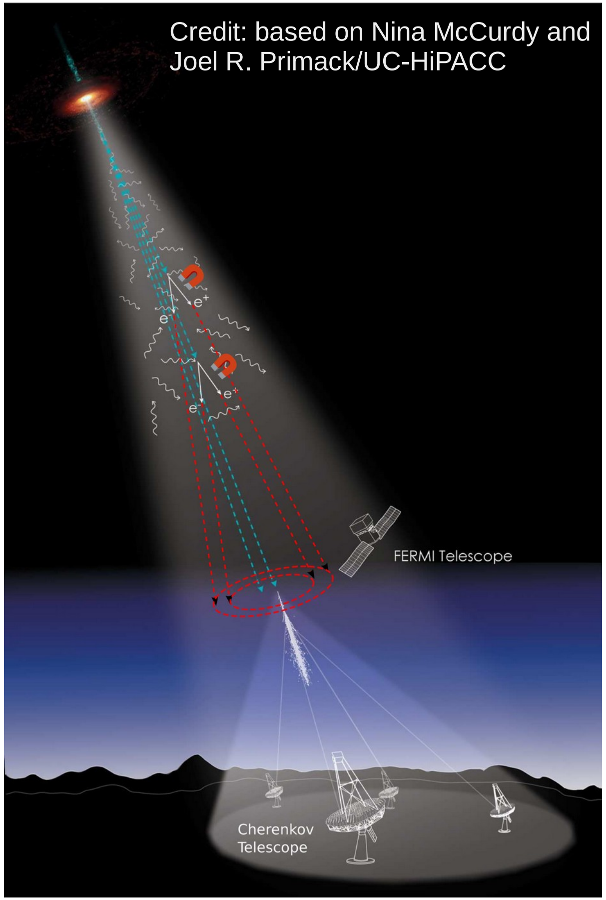

PSF profile with the expected signature of EGMF (Da Vela 2015)

No evidence of MBC observed with IACTs yet

Set upper limits on EGMF

e.g. VERITAS, ApJ, 835, 288 (2017)

- $\log_{10}B$ [G] < -14.3


Credit: based on Nina McCurdy and Joel R. Primack/UC-HiPACC

Probing EGMF in cosmic voids with gamma-rays

A relatively low magnetic field in voids should lead to an observed excess of gamma-rays of sources behind voids

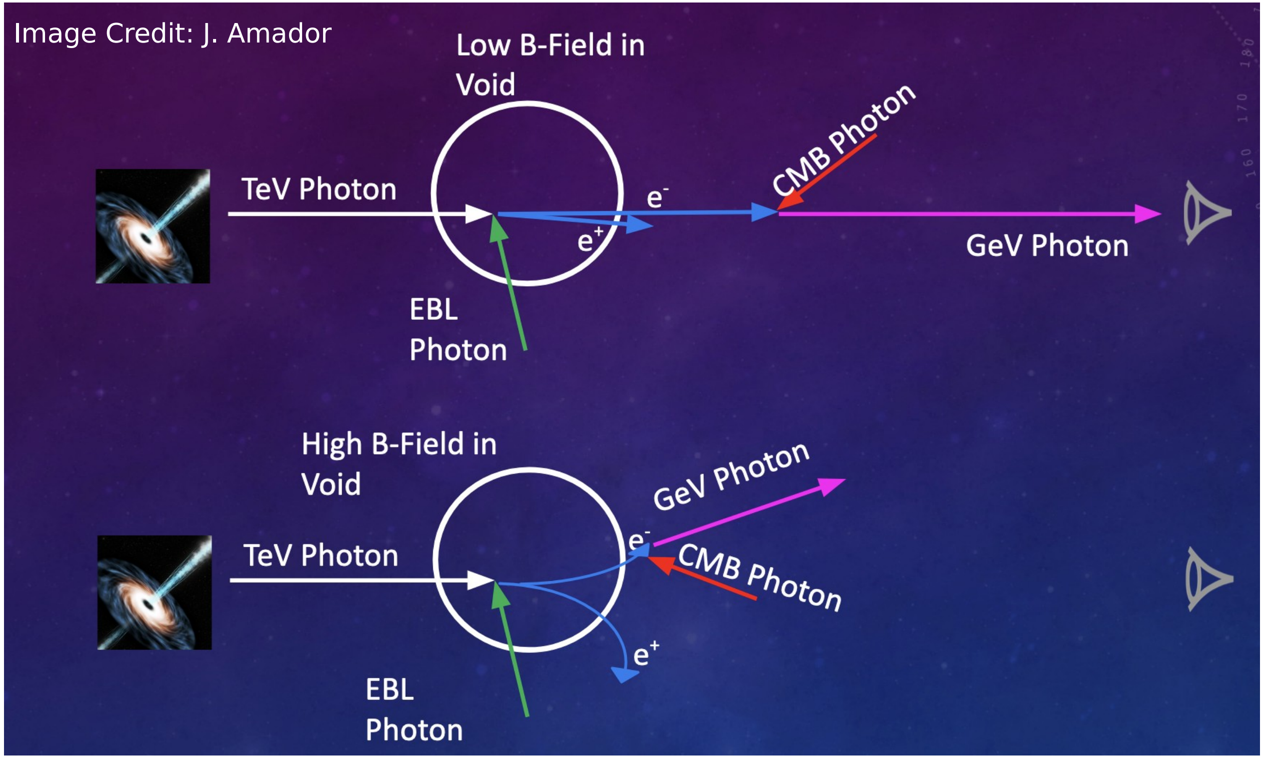


Image Credit: J. Amador

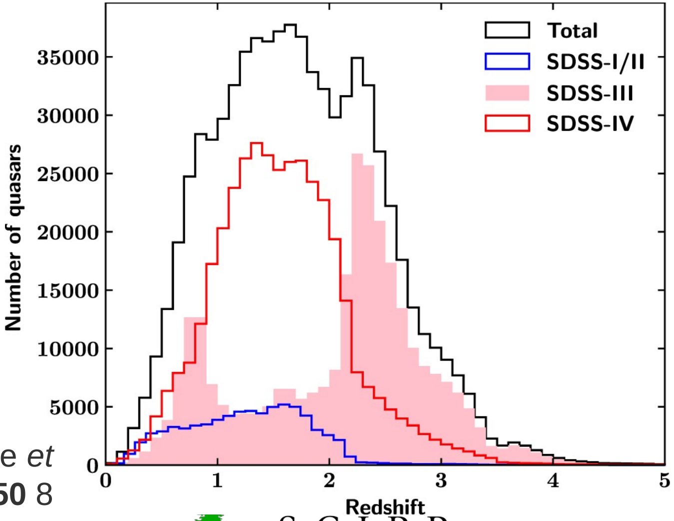
A Study on the Line of Sight to Galaxies Detected at Gamma-ray Energies

Next slides show results of a submitted paper to ApJL
(A. Furniss, J. N. Amador, O. Hervet, D. A. Williams)

- Is there more voids in front of Gamma-ray blazars than optical quasars?
- Comparing two populations from Fermi-LAT detected blazars (4LAC-DR3, E>100 MeV) and SDSS-DR9 quasars
- Only considering sources within the SDSS void footprint
- $0.1^{*} < z < 0.7$
  - The redshift lower limit is due to low voidiness bias for nearby sources
- We split the sample in two populations:
  - Nearby ($0.1 <= z < 0.4$)
  - Distant ($0.4 <= z < 0.7$)

Population	Reference	Catalog Non-Duplicated Total	$z < 0.7$	$0.1 \leq z < 0.4$	$0.4 \leq z < 0.7$
4LAC DR3	Ajello et al. (2022)	3,472	328	160	143
SDSS QSOs	Lyke et al. (2020)	797,606	19,796	3,326	16,425

Full SDSS sample

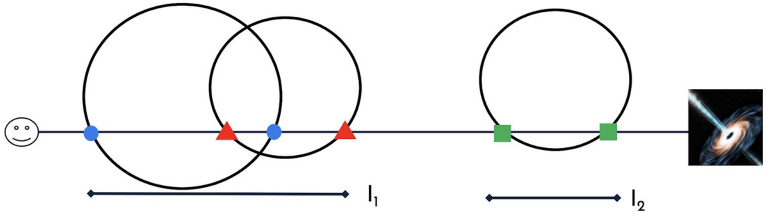


From Brad W. Lyke *et al* 2020 *ApJS* **250** 8

Voidiness and z-matched population

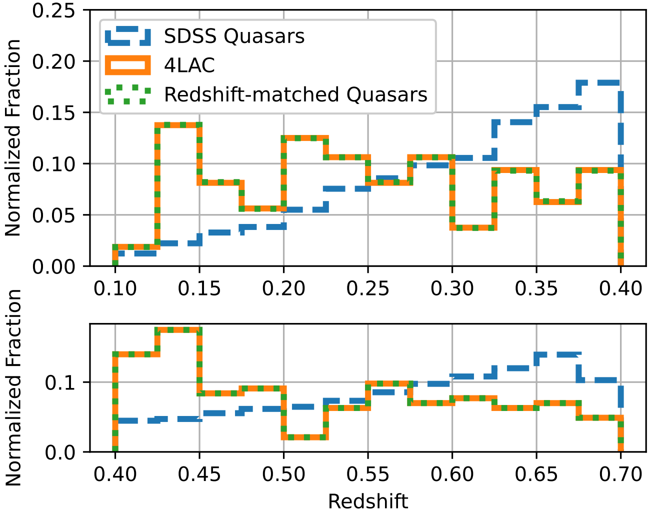
For each source, we estimate the “Voidiness” (V) as the fraction of the line of sight which passes through a void

$$\mathbf{V} = \frac{\mathbf{D_{Void}}}{\mathbf{D_{LoS}}}$$

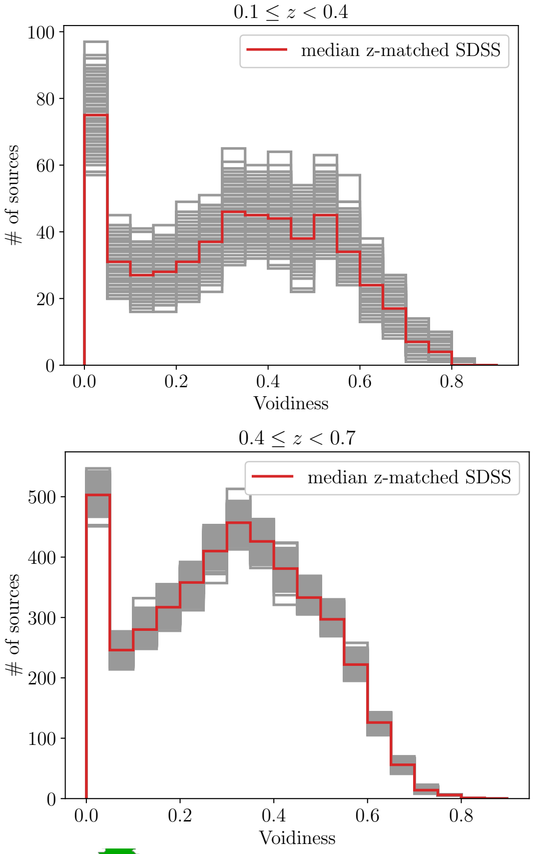


SDSS-QSOs and 4LAC have a large difference in their redshift distribution

We want to remove any redshift/voidiness correlation bias from our test, and randomly carve the SDSS population to match the redshift distribution of the 4LAC



500 randomized z-matched sample selection



How SDSS and Fermi samples compare to randomized sky locations?

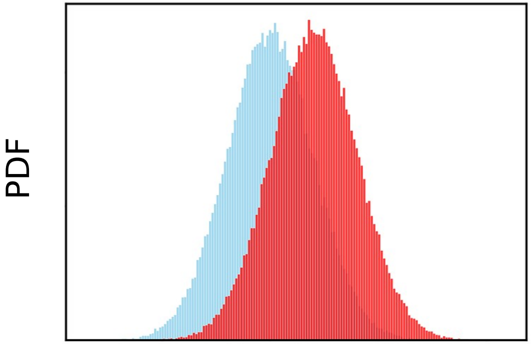
- Produce randomized populations from the filtered populations
- keep redshift information
- assign random locations within SDSS footprint
- 500 random simulations for both optical and gamma-ray populations, respectively
- Utilize Kolmogorov-Smirnov Test (KS test) to understand data drift of voidiness profile

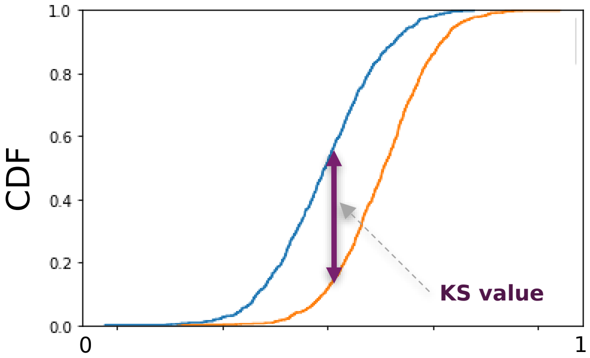
Outputs

KS Statistic: a numerical value between 0 and 1, representing the maximum difference between two cumulative probability distributions (CDFs).

P-value (2 sample test): Probability that the two tested samples are drawn from the same underlying continuous distribution.

example





How SDSS and Fermi samples compare to randomized sky locations

Optical quasars do not appear to be randomly distributed in space.
Two bands for comparison:
“Nearby”: 0.1 <= z < 0.4
- Median KS statistic: 0.056
- Median p-value 4.6 X 10^{-5}

“Distant”: 0.4 <= z < 0.7
- Median KS statistic 0.095
- Median p-value 2.4 X 10^{-65}

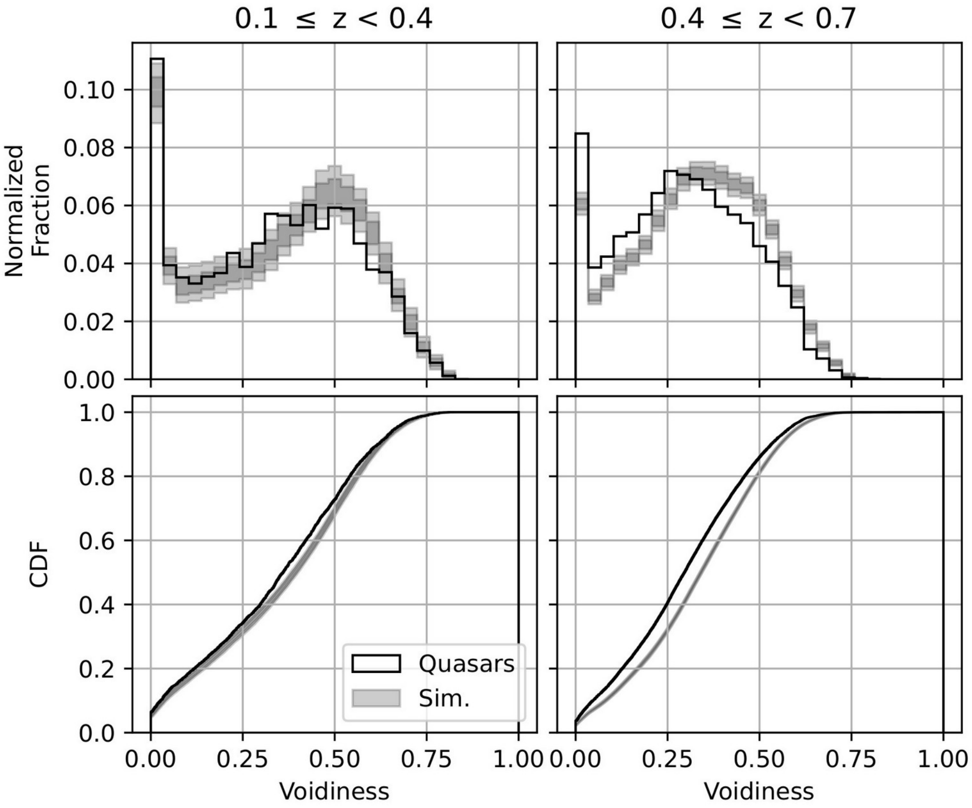
Result is not surprising – we know galaxies are not randomly distributed in the Universe!

Gamma-ray quasars are consistent (within 2 sigma) with random distributions
“Nearby”: 0.1 <= z < 0.4
- Median KS statistic: 0.11
- Median p-value 0.39

“Distant”: 0.4 <= z < 0.7
- Median KS statistic 0.13
- Median p-value 0.21

Too small population to efficiently reject random distribution?

SDSS QSOs



Voidiness of optical quasars vs gamma-ray blazars

No significant discrepancy in the 0.1-0.4 redshift range:

Voidiness average :

- SDSS: 0.33
- 4LAC: 0.32

KS test:

- Median KS statistic: 0.076
- Median p-value 0.45

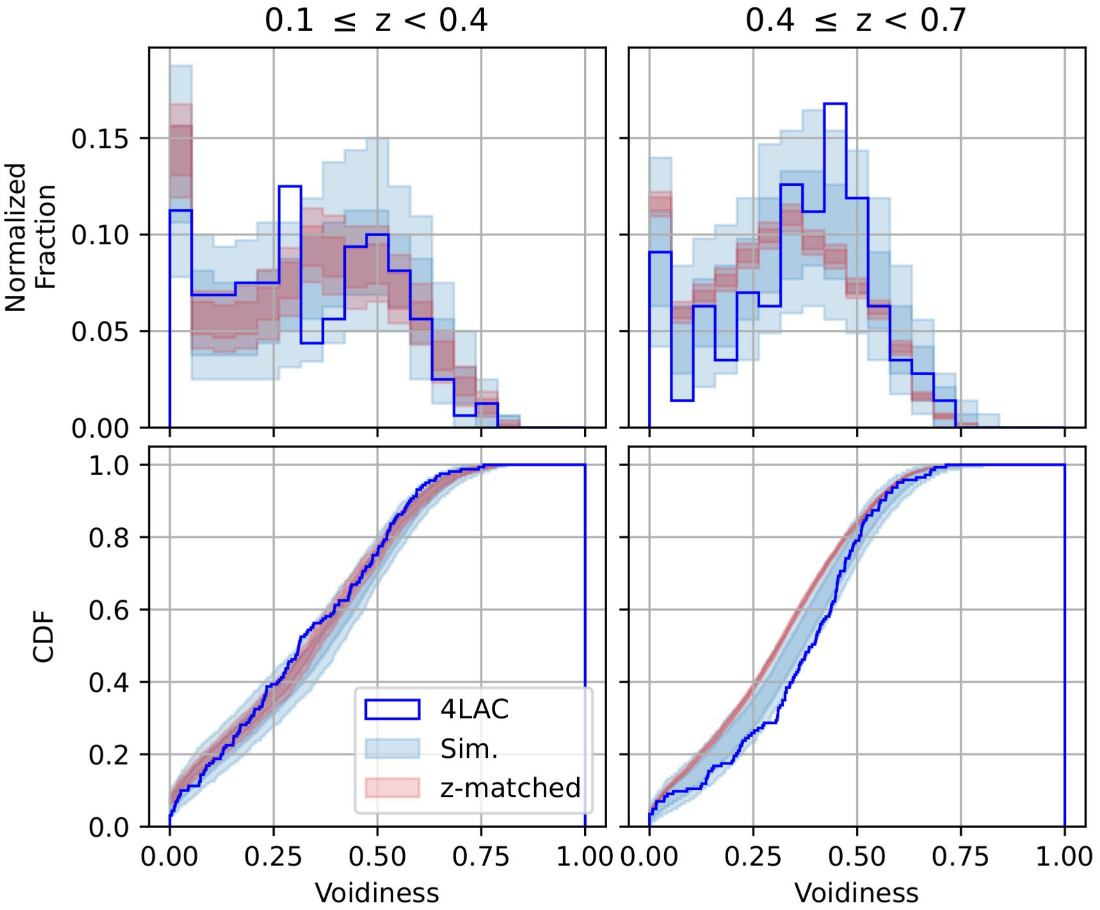
Significant discrepancy in the 0.4-0.7 redshift range:

Voidiness average :

- SDSS: 0.31
- 4LAC: 0.36

KS test:

- Median KS statistic: 0.056
- Median p-value: 2.3×10^{-5} (4.1σ)



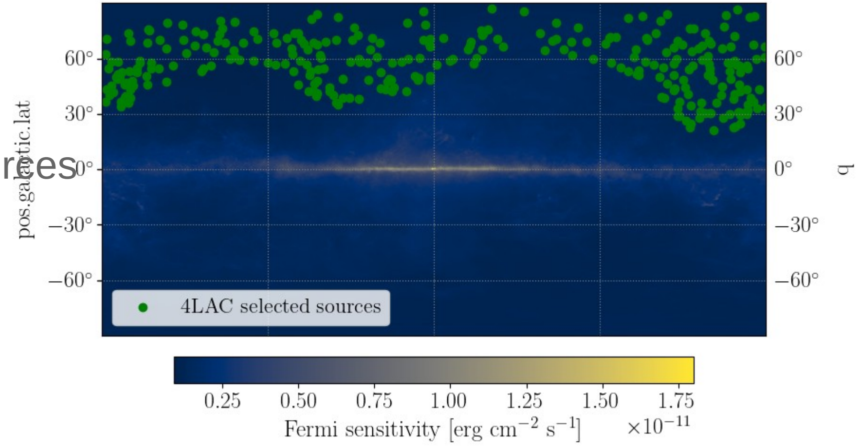
Discussion

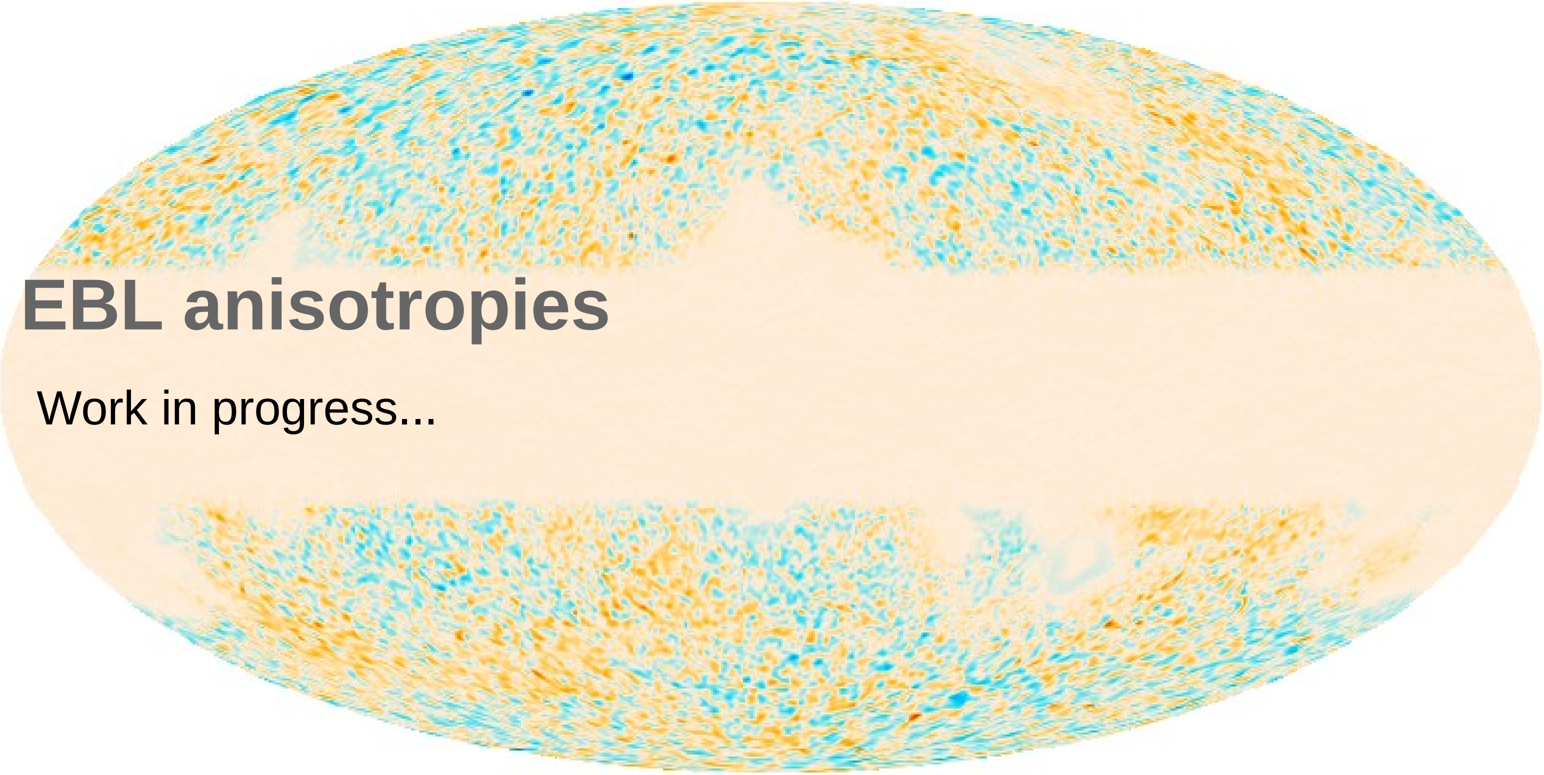
- SDSS-QSOs are not randomly distributed on the sky
- 4LAC blazars are consistent with random distribution (sample limited)
- 4LAC blazars shows higher voidiness in $0.4 < z < 0.7$ with a significantly different voidiness distribution deviating at the 4 sigma level

This result lead to multiple questions:
- Why these two samples have different voidiness distribution?
- Why only in the 0.4-0.7 redshift range and not in the 0.1-0.4?
- Can this difference be solely explained by lower EGMF in cosmic void?
- Are we sure EBL anisotropies do not matter?

-Is there any selection/detection bias in the catalogues?
Checked for Fermi 4FGL-DR3 sensitivity vs voidiness...

Most sensitive regions are weakly linked with lower voidiness sources ~1.5 sigma level. Does not support a sensitivity effect favouring higher voidiness





Part II: EBL anisotropies

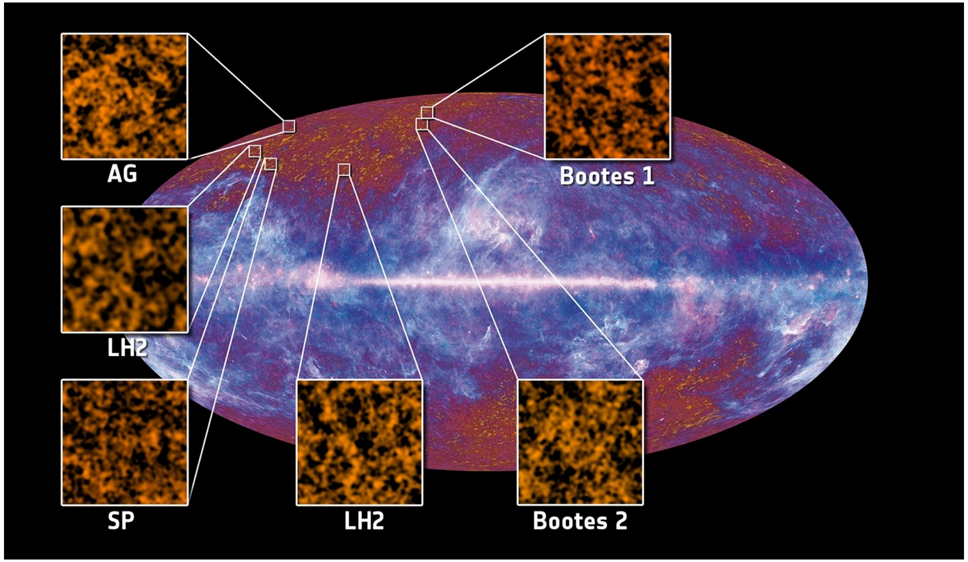
Work in progress...

CIB smoothed map at 857 GHz *(Planck Collaboration 2016)*

Known small scale EBL anisotropies

Planck CIB anisotropy measured from 10’ to 2deg .
ΔI/I=15% from 217 to 857 GHz.

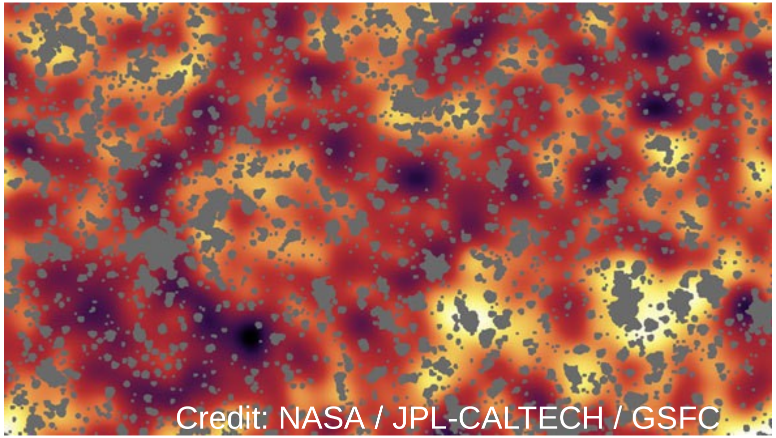
(Planck Early Results XVIII, 2018)



Location of the first six fields used to detect the Cosmic Infrared Background anisotropies. Credit: ESA/Planck Collaboration

CIB observed by Spitzer in 2006

(H. Dole et al.,2006)



Credit: NASA / JPL-CALTECH / GSFC

Fantastic results, but

- Narrow bands of the CIB spectrum
- Very challenging foreground emission (galactic dust)
- Small sky area

Can gamma-rays help?

Model-dependent measurement of the EBL opacity

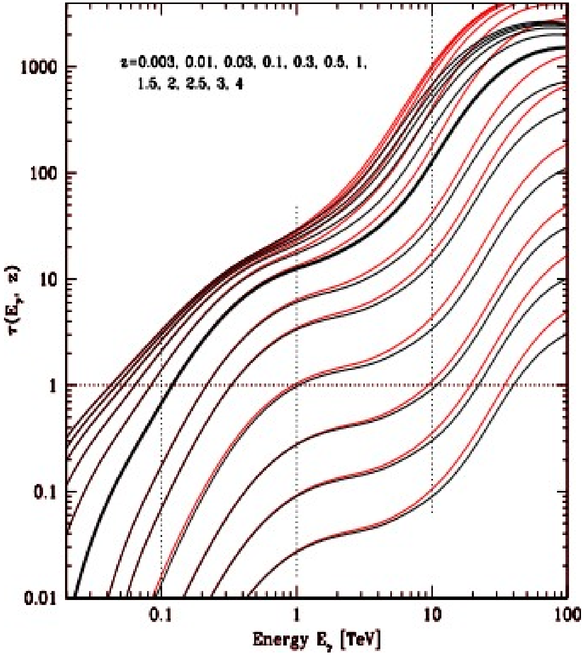
Observed spectra are fitted with an EBL-absorbed power-law-like model and an opacity factor α:

$$\Phi_{obs} = e^{-\alpha\tau(E,z)}\Phi_{intr}$$

Φ_{obs} : Observed spectrum Φ_{intr} : Intrinsic spectrum

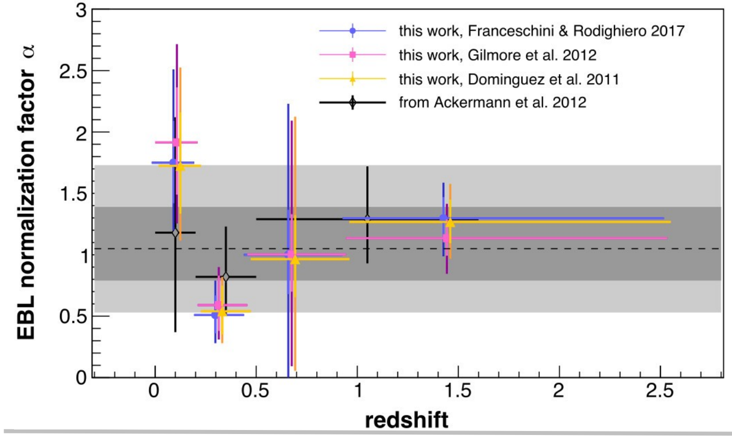
$\tau(E,z)$: EBL opacity (model dependent approach)

α : Opacity factor → Value to probe!



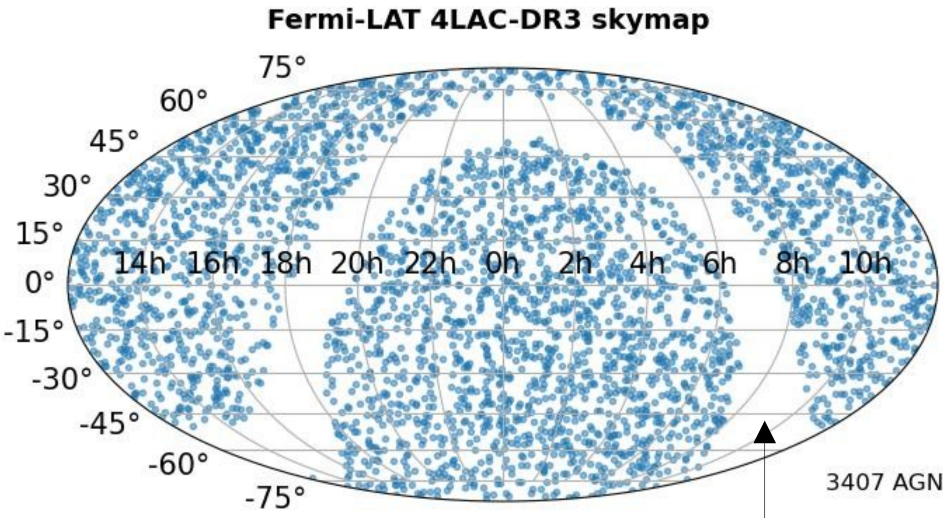
EBL opacity
(Franceschini & Rodighiero 2017)

Systematics are estimated from different choice of EBL nominal model



Biasuzzi et al. 2019

Gamma-ray sources are now fully mapping the sky

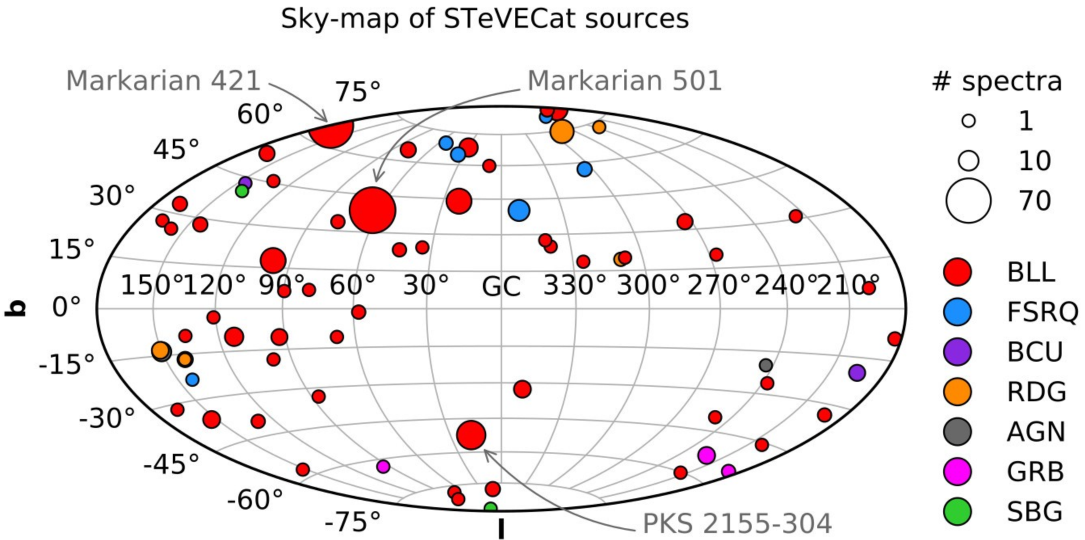


Celestial coordinates

Galactic plane

STeVECat, the Spectral TeV Extragalactic Catalog

(Greaux et al. ICRC 2023)



Galactic coordinates

403 spectra from 73 sources
350 spectra without time overlap

General concept

- Each extragalactic gamma-ray source provides information on the EBL opacity along the line of sight
- Individual source might not be constraining enough to probe for small scale anisotropy, but multiple sources should provide large-scale opacity constraints → the more the better
- To reduce the number of free parameters we use an EBL model-dependent method (*mostly Saldana-Lopez 2021 for this presentation)*

Spectral models tested:

Absorbed Power-Law (3 free par.)

$$\Phi_{PL,abs}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-\alpha\tau(E,z)}$$

Absorbed Power-Law with exponential cutoff (4 free par.)

$$\Phi_{EPL,abs}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-E/E_{cut}} e^{-\alpha\tau(E,z)}$$

Absorbed Log Parabola (4 free par.)

$$\Phi_{LP,abs}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma-\beta\log(E/E_0)} e^{-\alpha\tau(E,z)}$$

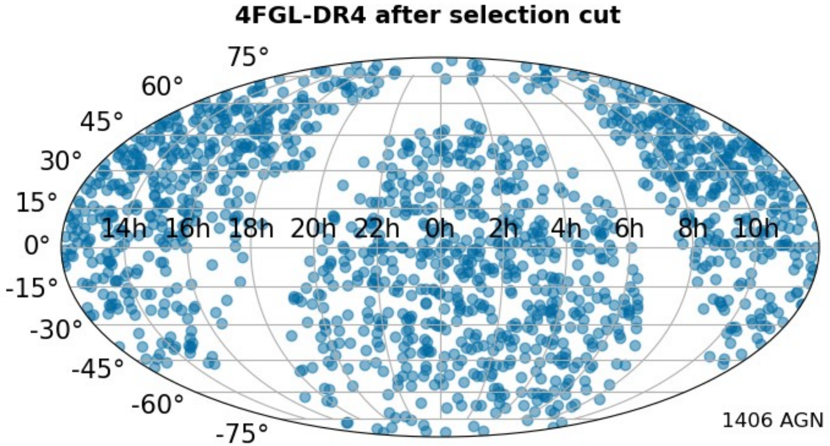
Absorbed Logparabola with exponential cutoff (5 free par.)

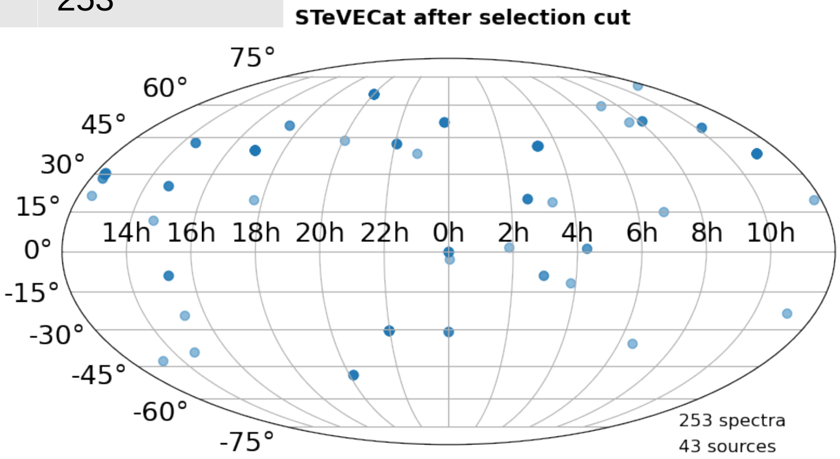
$$\Phi_{ELP,abs}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma-\beta\log(E/E_0)} e^{-E/E_{cut}} e^{-\alpha\tau(E,z)}$$

Simpler hypothesis is rejected at a 2 sigma level (see Biasuzzi et al. 2019)

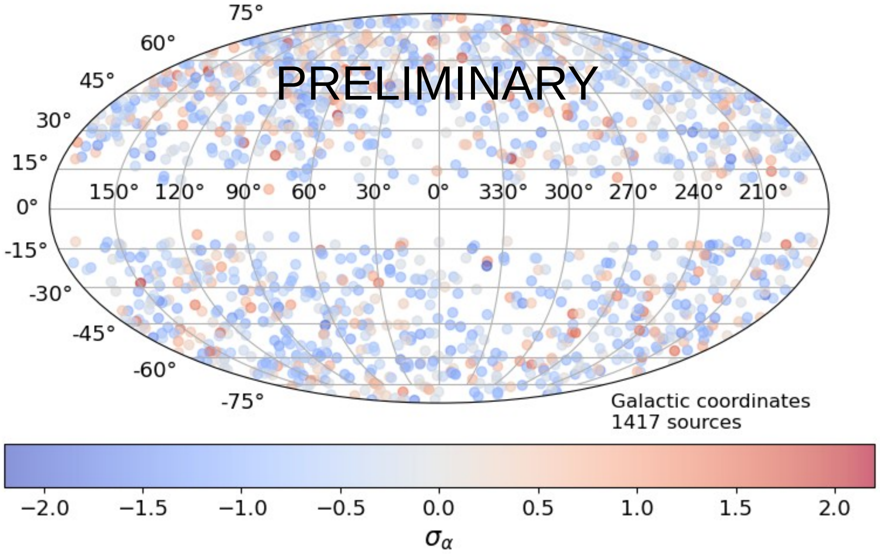
Spectra selection

	4FGL-DR4	STeVECat
Extragalactic spectra	3383	350
And redshift	1500	310
And >= 4 points (4FGL U.Ls included)	1500	282
And probing EBL opacity Tau >= 0.05	1479	268
And no convex curvature (>1 sigma)	1450	253
Do no fail spectral fit	1406	253

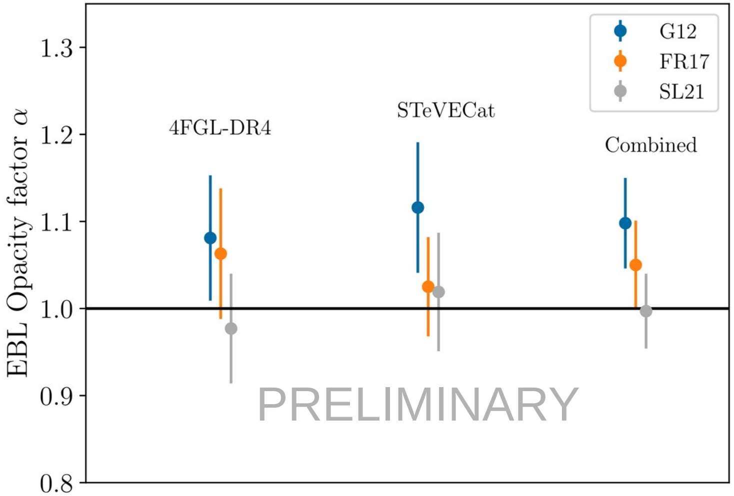




General opacity measurements



Combined likelihood with all spectra



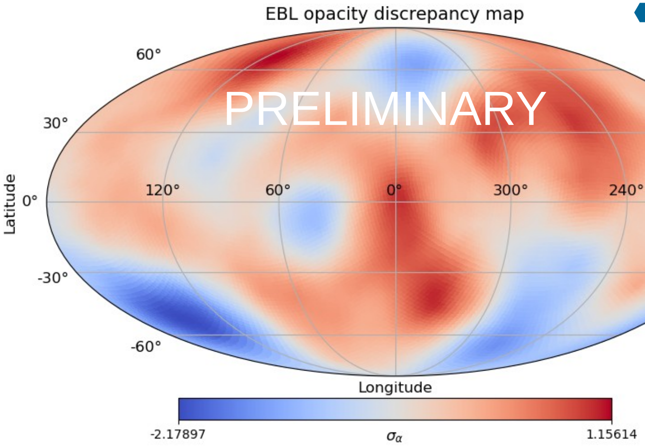
- Map of discrepancy with SL21 EBL model
- All spectra and all individual sources' combined spectra in agreement with EBL models (<3 sigma discrepancy)

- Combined 1659 spectra (1417 sources)
- Probing opacity level down to $\Delta\alpha/\alpha < 5\%$

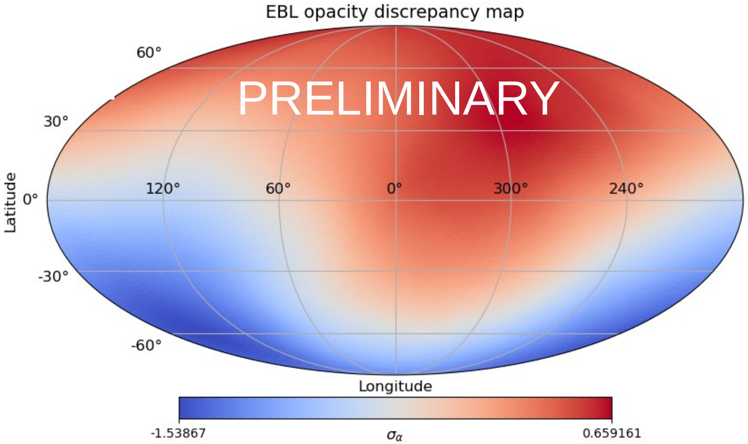
Producing EBL opacity discrepancy maps

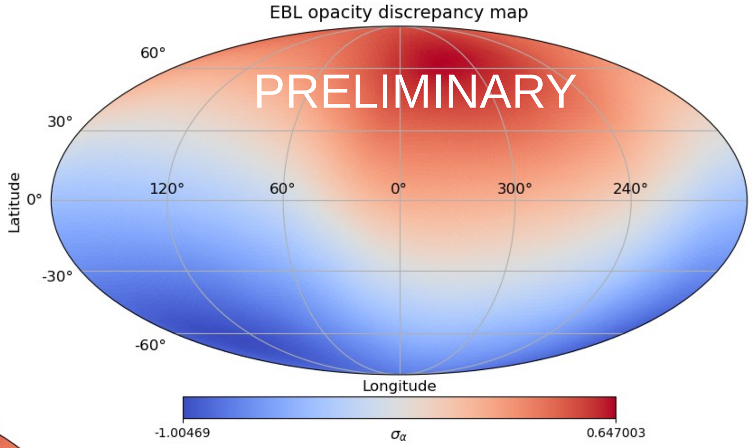
- Top-hat moving average (combined likelihood) with carious cone radii
- All 1659 spectra are included in these maps

Cone radius = 20 deg



Cone radius = 60 deg

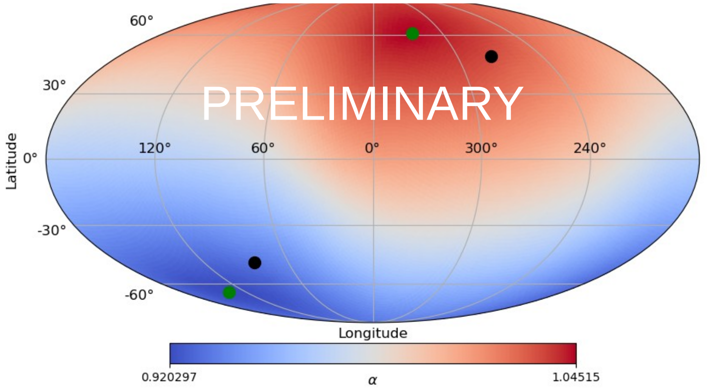




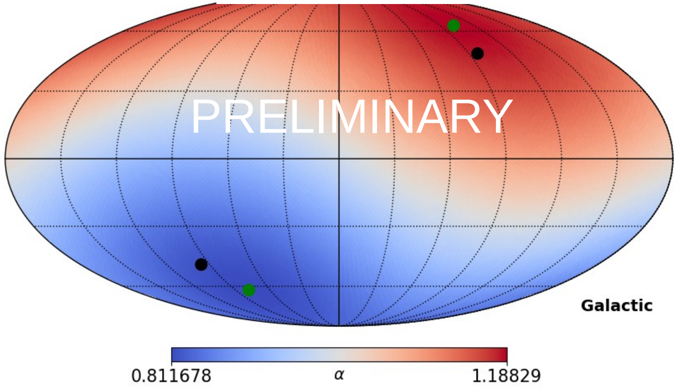
Cone radius = 90 deg

Probing for an EBL dipole

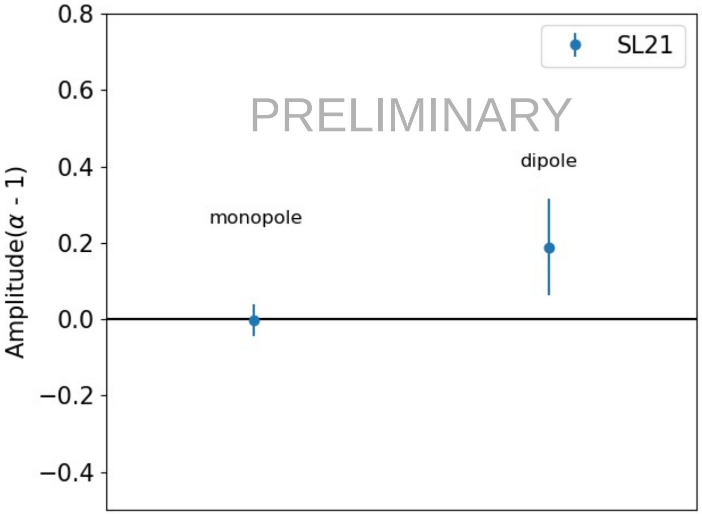
Smoothed average map



Fitted dipole



Result of fitting a dipolar spherical harmonic (m,l = 0,1) from individal sources likelihood profiles with free rotational vectors



Black points: CMB dipole
Green points: Extremums of the EBL maps

- No significant dipole measured (1.5 sigma)
- Systematics not included yet

Conclusion

- Thanks to Fermi and VHE catalogs, we have now access of thousands of gamma-ray spectra with associated redshift
- We reached a statistical theshold for precise investigations on cosmological variations over different line of sights (voids, EBL fluctuations,...)
- Recent and future VHE experiments (e.g. LHAASO, CTAO)would provide unprecendented constraints on cosmological anisotropies characterization